Chapter 1

Radiation

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Contents

Introduction

Radiation in growth chambers, as in the field, is the sole source of energy for plant growth and development. The effect of radiation on plants has been the subject of countless studies in photosynthesis, photomorphogenesis, and bioenergetics. Our intent is not to provide exhaustive coverage of plant response to radiation, but to provide a general discussion emphasizing the sources, applications, measurements, terminology, and reporting, with sufficient detail to allow a more complete understanding and utilization of the radiation environment in plant growth chambers. The terminology and units defining radiation and its effects on plants can be found in the glossary at the end of this chapter.

Characteristics

Radiation is propagated through space in waves but exists as discrete energy packets (photons) and has the relation of $E = h^*c/w$; where $h = 6.626 \cdot 10^{34}$ J·s (Planck's constant) and $c = 2.998 \cdot 10^{8}$ m·s^{-1} (speed of light) and w = wavelength in m. Thus, E is the energy of a photon at a single wavelength, or a quantum, in units of Joules (J). For a given amount of energy, the number of photons increases as the wavelength increases. For example, a given energy in the blue wavelengths (400 to 500 nm) has fewer photons than an equal energy in the red wavelengths (600 to 700 nm). Figure 1 shows the energy of photons (quanta) as a function of wavelength from 300 to 800 nm.

All energy in the electromagnetic spectrum travels at the speed of light and is termed radiation. This includes cosmic rays, gamma rays, X rays, ultraviolet, visible light (blue, green, yel-

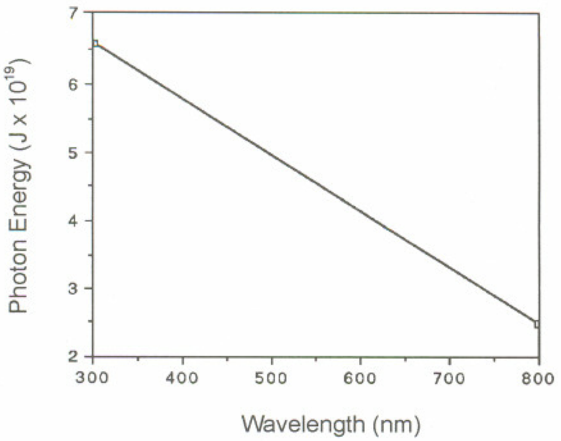


Figure 1. Photon energy as a function of wavelength.

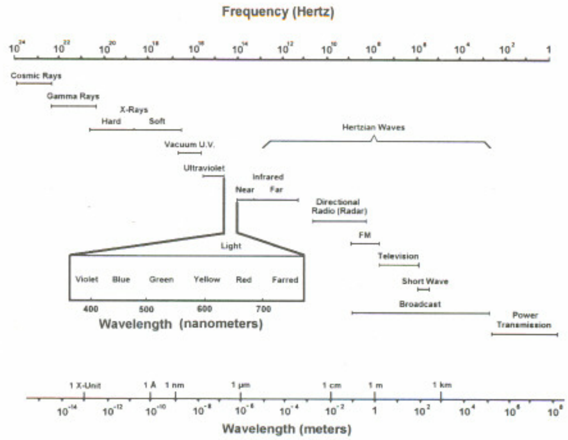


Figure 2. The electromagnetic spectrum.

low, and red), infrared, radar, radio and TV signals, power transmission, and all heat (Fig. 2).

Light is defined as radiation that stimulates the sensation of vision in the normal human eye, the photoptic response. This response range is nominally from 380 nm to 720 nm with a peak response at 550 nm. Figure 2 shows the electromagnetic spectrum, of which light is only a small segment. Thus, the word "light" is strictly defined and should be limited in usage to only the human physiological response. In many texts, as in the nonscientific vernacular, a modified definition of the word "light" has been adopted, meaning all visible radiation plus the adjacent regions of infrared (700 to 800 nm) and ultraviolet (400 nm). In this text, we will use radiation as the preferred term to describe the transfer of all types of energy and adhere to the definition of light as only a human response. We will, however, refer to the human chromatic response, color, to define perception of the general region of the electromagnetic spectrum in question, where blue is 400 to 500 nm, green is 500 to 600 nm, red is 600 to 700 nm, and farred is 700 to 800 nm.

Terminology and Units

The terminology and units for describing the effects of radiation on plants is constantly being revised as photobiological responses are better understood and new instruments are developed to incorporate this improved knowledge. Detailed terminology for monitoring radiation can be obtained in the IES Lighting Handbook (1993), Lighting for Plant Growth (Bickford and Dunn, 1972), and useful terminology for plant irradiation is discussed by Holmes et al. (1985) and Thimijan and Heins' (1983). Recommendations are provided in a publication by CIE (Tibbitts, 1993).

Photosynthetically active radiation (PAR) is a term used to describe radiation in wavelengths useful for photosynthesis of plants. PAR is generally accepted to be wavelengths between 400 and 700 nm, although it sometimes is defined to include wavelengths as short as 350 nm and as long as 850 nm. The specific quantity of radiation should be reported as moles of photons or energy. The radiation should be reported in terms of the quantity received per unit of time (usually a second) or the amount per day (24-hour period). Additionally, in certain experiments the amount for the entire experimental period is reported.

Radiation should be measured and reported in terms of photons and, in some studies, also in energy units. Measurements to define levels for photosynthesis should be stated in photons. Measurements to define levels for photomorphogenesis are commonly reported as energy units, but photon measurements are recom-

Table 1. Terminology and Units for Reporting Radiation Measurements

Broad band instruments (PAR meters and radiometers)[a]		
	Photons	Energy
Instantaneous	µmol $m^{-2}s^{-1}$	W m^{-2} or J $m^{-2}s^{-1}$
Daily	mol m^{-2} day^{-1}	J m^{-2} day^{-1}
Experiment	mol m^{-2} ($duration^{-1}$)	J m^{-2} ($duration^{-1}$)

Narrow band instruments (spectroradiometers)[b]		
	Photons	Energy
Instantaneous	µmol $m^{-2}s^{-1}$ nm^{-1}	W m^{-2} nm^{-1}
Daily	mol m^{-2} day^{-1} nm^{-1}	J m^{-2} day^{-1} nm^{-1}
Experiment	mol m^{-2} nm^{-1}	J m^{-2} ($duration^{-1}$) nm^{-1}

[a] The wavelength interval being measured must be indicated.
[b] The wavelength step width used must be indicated.

mended. Levels for the heating capacity of the radiation should be defined as energy units. The radiation sometimes is reported for historical reasons as light units, representing the brightness of the radiation to the human eye. Recommended terminology and units for reporting measurements with broad band (PAR meters and radiometers) and narrow band (spectroradiometers) instruments are given in Table 1.

When a flat (cosine-corrected) sensor is used, the radiation should be reported as "the photosynthetic photon flux (PPF) for the (400-700) nm waveband was (xxx) µmol m^{-2} s^{-1}." When a spherical sensor is used, the radiation should be reported as "the photosynthetic photon fluence rate (PPFR) for the (400-700) nm waveband was µmol m^{-2} s^{-1}." Note that the units of these measurements are identical. It is essential therefore that the sensor type be given (PPFR could be as much as four times the PPF if measured in a uniform radiation field).

Conversion of Units

The conversion of measurements from photons to energy or vice versa cannot be accomplished accurately unless measurements are made with a spectroradiometer and the values for each separate wavelength are known. Then the radiation formula shown on the first page of this chapter can be utilized for each wavelength step and summed in stepwise fashion. If broad bandwidth measurements are taken, however, as with a PAR sensor, then conversions can only be approximate. Several different scientists (McCree, 1972b; Thimijan and Heins, 1983) have published approximate conversions for different lamp types as shown in Table 2 of this chapter. These are approximate because the spectral output of sources varies with individual luminaires, lamps, and ballasts, and with their hours of use.

Plant Responses

Photosynthesis

Radiation is the energy source for photosynthesis, the primary process through which energy is fixed on earth. Radiation controls pho-

Table 2. Approximate[a] conversion values for radiation of 400-700 nm from different sources. (Adapted from Thimijan and Heins, 1983.)

Radiation Source	Multiply by Indicated Value					
	Photons to Wm^{-2}	Wm^{-2} to Photons	Photons to lux[b]	Lux[b] to Photons	Wm^{-2} to lux[b]	lux[b] to Wm^{-2}
Sunlight	0.219	4.57	54	0.019	0.249	4.02
Cool white fluorescent	0.218	4.59	74	0.014	0.341	2.93
Plant growth fluorescent[c]	0.208	4.80	33	0.030	0.158	6.34
High-pressure sodium	0.201	4.98	82	0.012	0.408	2.45
High-pressure metal halide	0.218	4.59	71	0.014	0.328	3.05
Low-pressure sodium	0.203	4.92	106	0.009	0.521	1.92
Incandescent 100W tungsten halogen	0.200	5.00	50	0.020	0.251	3.99

[a] Values vary depending on luminaire, lamp, ballast, and hours of use
[b] Multiply lux times 93.02 to obtain foot candles
[c] GTE Gro-Lux

tosynthesis not only through its intensity, but also through the wavelengths available and the duration or time it is present. The radiation level adequate to saturate the photosynthetic system for many plants with the C-3 carbon capture system is commonly about 400 µmol m^{-2} s^{-1} when provided for 16 hours during each daily period. Some high-irradiance plants, particularly those with C-4 photosynthetic systems, require levels of at least 500 µmol m^{-2} s^{-1} or much higher for a 16-hour daily period to maximize growth. Slow-growing foliage plants will succeed with as little as 10 to 50 µmol m^{-2} s^{-1} for an 8-hour daily period and will fail with higher levels. Generally, if the photoperiod is extended or decreased and the irradiance varied proportionately so that the (irradiance · time) products are a constant value, growth rates will be similar (reciprocity holds true).

Low irradiance levels on most plants lead to (a) smaller leaves with a greater length-to-width ratio, (b) elongation of internodes, (c) reduced concentration of chlorophyll, and (d) less dry weight at particular stages of maturity. In contrast, high irradiance levels lead to the stimulation of auxiliary branch growth, proliferation of growing points, possible photodestruction of chlorophyll (bleaching), and stress symptoms attributed to spectral radiation excesses, such as increased anthocyanin production. High irradiance levels also cause significant heating of leaves so that water loss is increased and may lead to desiccation and eventual necrosis.

The photosynthetic reaction is driven by radiation in the spectral region between 400 and 700 nm. Radiation in this region has been defined as photosynthetically active radiation (PAR) (McCree, 1972a). Photons at all wavelengths within this range are not equally effective in producing photosynthesis in intact plants, as seen in the quantum efficiency curve shown in Fig. 3 (McCree, 1972a). For wavelengths between 400 and 600 nm, efficiency decreases slightly, between 10 and 25% for different plant species. The greatest decreases are between 500 and 600 nm. Radiation in this region is not absorbed well by chlorophyll; instead, some is reflected, giving plants the characteristic green appearance. If accurate spectral data is obtained for irradiance provided to plants in a particular chamber, it is possible to calculate the relative photosynthetically effective photon flux of a particular radiation source by multiplying (convoluting) the radiation spectral value by the relative quantum efficiency at each wavelength. These relative quantum efficiencies, determined from published data (McCree, 1972a), have been interpolated for each 2 nm waveband over the photosynthetic spectrum and are provided in Table 3 (Sager et al., 1988). Studies of photosynthetic reactions of extracted chlorophyll have led some scientists to the false conclusion that photosynthetic efficiency is proportional to the chlorophyll absorption spectrum. Radiation absorbed by other pigments, however, primarily the carotenoids and phycobilins, also results in photosynthesis when the absorbed energy is transferred to chlorophyll. Photosynthetic, or plant growth, action spectra are complex sum-

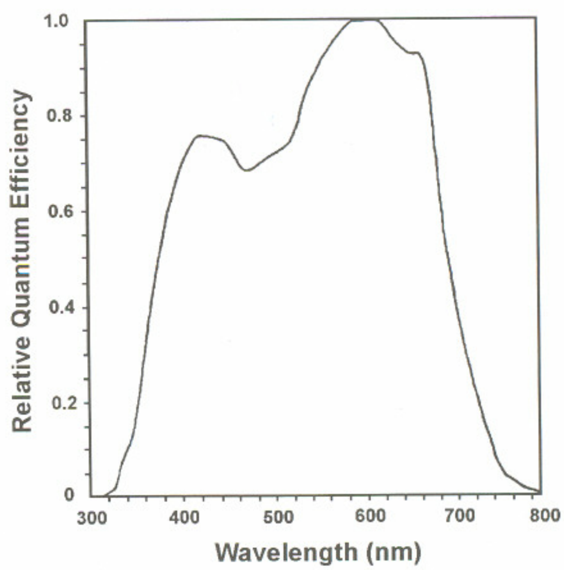


Figure 3. Normalized relative photosynthetic response action for photons as a function of wavelength.

Table 3. Spectral files of relative quantum efficiency[a] (RQE); phytochrome red absorbing state[b] (A_r), phytochrome farred absorbing state[b] (A_{fr}); and photochrome photochemical cross sections, red absorbing state (σ_r), farred absorbing state (σ_{fr}), at 2nm wavelength intervals (λ) from 300 to 800 nm.

λ	RQE	A_r	A_{fr}	σ_r $m^2\ mol^{-1}$	σ_{fr} $m^2\ mol^{-1}$
300	0	0.4	0.39	2233	920
302	0	0.33	0.33	1838	784
304	0	0.3	0.29	1656	706
306	0	0.27	0.28	1499	668
308	0	0.25	0.27	1412	645
310	0	0.23	0.25	1294	610
312	0	0.22	0.25	1221	599
314	0	0.2	0.23	1127	569
316	0.01	0.18	0.22	1029	534
318	0.01	0.17	0.21	953	505
320	0.01	0.16	0.19	893	468
322	0.01	0.15	0.18	834	432
324	0.01	0.14	0.16	767	393
326	0.02	0.13	0.15	747	369
328	0.03	0.13	0.14	726	340
330	0.04	0.13	0.13	713	319
332	0.05	0.13	0.13	713	308
334	0.07	0.13	0.12	725	285
336	0.08	0.13	0.12	751	281
338	0.09	0.14	0.11	780	266
340	0.1	0.14	0.11	811	259
342	0.11	0.15	0.11	841	257
344	0.12	0.16	0.11	879	255
346	0.13	0.17	0.11	952	252
348	0.14	0.18	0.12	989	257
350	0.16	0.19	0.12	1048	261
352	0.18	0.2	0.12	1124	271
354	0.2	0.21	0.13	1190	274
356	0.22	0.22	0.13	1263	282
358	0.25	0.24	0.13	1326	291
360	0.27	0.25	0.14	1389	301
362	0.3	0.26	0.14	1436	312
364	0.33	0.26	0.15	1468	326
366	0.35	0.26	0.15	1484	335
368	0.38	0.27	0.16	1517	349
370	0.4	0.27	0.17	1529	365
372	0.42	0.27	0.17	1540	381
374	0.44	0.28	0.18	1545	397
376	0.46	0.28	0.18	1577	411
378	0.48	0.28	0.19	1577	426
380	0.5	0.28	0.2	1586	442
382	0.52	0.28	0.2	1572	451
384	0.54	0.28	0.2	1557	464
386	0.55	0.27	0.21	1505	485
388	0.57	0.26	0.21	1464	496
390	0.59	0.25	0.22	1381	511
392	0.6	0.23	0.22	1294	524
394	0.62	0.22	0.22	1215	534
396	0.63	0.2	0.22	1097	540
398	0.65	0.18	0.23	1004	553
400	0.66	0.16	0.23	904	559
402	0.67	0.14	0.23	810	563
404	0.68	0.13	0.23	733	568
406	0.69	0.12	0.23	668	571
408	0.7	0.11	0.22	604	573
410	0.71	0.1	0.22	561	570
412	0.72	0.09	0.22	519	564
414	0.73	0.08	0.22	471	557
416	0.74	0.08	0.21	427	543
418	0.74	0.07	0.2	408	528
420	0.75	0.07	0.2	366	507
422	0.75	0.06	0.19	348	489
424	0.76	0.06	0.17	320	454
426	0.76	0.05	0.17	308	431
428	0.76	0.05	0.16	292	401
430	0.76	0.05	0.15	274	377
432	0.76	0.05	0.14	263	353
434	0.76	0.04	0.13	244	325
436	0.75	0.04	0.12	244	300
438	0.75	0.04	0.11	230	273
440	0.75	0.04	0.1	230	261
442	0.75	0.04	0.09	209	233
444	0.75	0.03	0.08	196	217
446	0.75	0.03	0.08	184	202
448	0.75	0.03	0.07	172	186
450	0.75	0.03	0.07	162	169
452	0.75	0.03	0.06	162	155
454	0.74	0.03	0.06	150	144
456	0.74	0.03	0.05	143	132
458	0.73	0.02	0.05	128	126
460	0.73	0.02	0.04	128	112
462	0.72	0.02	0.04	119	106
464	0.71	0.02	0.04	119	99.1
466	0.7	0.02	0.04	107	93.1
468	0.7	0.02	0.03	107	87.7
470	0.69	0.02	0.03	101	81.9
472	0.69	0.02	0.03	101	75.7
474	0.68	0.02	0.03	92.9	72.2
476	0.68	0.02	0.03	92.9	71.8
478	0.68	0.02	0.02	84.6	62.5
480	0.69	0.02	0.02	84.6	57.8
482	0.69	0.02	0.02	84.6	53.1
484	0.69	0.01	0.02	74.8	49.6
486	0.69	0.01	0.02	74.8	49.6
488	0.69	0.01	0.02	74.8	49.6
490	0.7	0.01	0.02	74.8	44.9
492	0.7	0.01	0.02	68.7	45.2
494	0.7	0.01	0.02	68.7	41.6
496	0.7	0.01	0.02	68.7	41.6
498	0.71	0.01	0.02	68.7	36.9
500	0.71	0.01	0.02	68.7	36.9
502	0.71	0.01	0.02	77	36.5
504	0.71	0.01	0.02	77	37.6
506	0.72	0.01	0.01	77	32.9
508	0.72	0.01	0.01	77	32.9
510	0.72	0.01	0.01	77	32.9
512	0.72	0.01	0.01	77	32.9
514	0.73	0.02	0.01	88.4	33.3
516	0.73	0.02	0.01	93.7	27.3
518	0.73	0.02	0.01	110	26.4
520	0.73	0.02	0.01	110	26.4
522	0.74	0.02	0.01	109	26.3
524	0.74	0.02	0.01	122	30.9
526	0.75	0.02	0.01	130	30.4
528	0.75	0.02	0.01	130	30.4

(Continued)

λ	RQE	A_r	A_{fr}	σ_r $m^2\,mol^{-1}$	σ_{fr} $m^2\,mol^{-1}$	λ	RQE	A_r	A_{fr}	σ_r $m^2\,mol^{-1}$	σ_{fr} $m^2\,mol^{-1}$
530	0.76	0.02	0.01	137	30	648	0.94	0.71	0.26	3982	485
532	0.77	0.03	0.01	153	29.2	650	0.94	0.76	0.27	4242	510
534	0.78	0.03	0.01	168	28.4	652	0.94	0.79	0.28	4444	531
536	0.8	0.03	0.01	168	28.4	654	0.93	0.83	0.3	4624	558
538	0.81	0.03	0.02	186	32.9	656	0.93	0.87	0.31	4887	587
540	0.82	0.04	0.02	202	32.1	658	0.93	0.91	0.33	5089	611
542	0.83	0.04	0.02	221	33.3	660	0.93	0.94	0.34	5250	634
544	0.84	0.04	0.02	239	32.3	662	0.93	0.97	0.35	5417	660
546	0.85	0.05	0.02	252	35.2	664	0.93	0.99	0.36	5535	680
548	0.86	0.05	0.02	270	34.3	666	0.93	1	0.37	5601	705
550	0.87	0.05	0.02	304	39.3	668	0.93	1	0.38	5582	724
552	0.88	0.06	0.02	311	39	670	0.93	0.99	0.38	5519	740
554	0.88	0.06	0.02	343	37.3	672	0.92	0.95	0.39	5322	754
556	0.89	0.07	0.02	369	43.9	674	0.92	0.91	0.39	5115	765
558	0.9	0.07	0.02	403	42.1	676	0.9	0.85	0.39	4764	784
560	0.91	0.08	0.03	421	45.8	678	0.88	0.78	0.38	4378	798
562	0.91	0.08	0.03	435	45.1	680	0.84	0.72	0.38	4052	809
564	0.92	0.08	0.03	468	49.9	682	0.8	0.64	0.38	3594	826
566	0.93	0.09	0.03	504	55.6	684	0.76	0.56	0.38	3119	842
568	0.93	0.09	0.03	523	54.6	686	0.71	0.48	0.37	2689	857
570	0.94	0.1	0.03	560	61.3	688	0.66	0.41	0.37	2307	878
572	0.94	0.11	0.03	595	59.5	690	0.61	0.34	0.37	1906	899
574	0.95	0.11	0.04	640	65.8	692	0.57	0.28	0.37	1563	917
576	0.95	0.12	0.04	679	69.5	694	0.53	0.23	0.38	1276	942
578	0.96	0.13	0.04	735	73.1	696	0.5	0.18	0.38	1014	965
580	0.96	0.14	0.04	789	76.7	698	0.47	0.14	0.39	809	994
582	0.97	0.15	0.05	844	80.7	700	0.44	0.12	0.4	649	1027
584	0.97	0.16	0.05	908	84.2	702	0.41	0.09	0.4	527	1054
586	0.98	0.17	0.04	967	93	704	0.39	0.08	0.41	427	1089
588	0.98	0.19	0.06	1052	95.1	706	0.37	0.06	0.43	331	1125
590	0.99	0.2	0.06	1122	99.7	708	0.34	0.05	0.43	277	1151
592	0.99	0.21	0.06	1201	110	710	0.32	0.04	0.45	236	1195
594	0.99	0.23	0.07	1304	121	712	0.31	0.03	0.46	187	1232
596	1	0.25	0.07	1381	124	714	0.29	0.03	0.48	169	1268
598	1	0.26	0.08	1477	136	716	0.27	0.03	0.49	147	1298
600	1	0.28	0.09	1576	146	718	0.25	0.02	0.5	135	1337
602	1	0.3	0.09	1665	148	720	0.24	0.02	0.51	117	1374
604	1	0.31	0.09	1745	157	722	0.22	0.02	0.53	103	1405
606	1	0.32	0.1	1815	161	724	0.21	0.02	0.54	103	1438
608	1	0.34	0.1	1894	171	726	0.19	0.02	0.55	92.1	1459
610	1	0.35	0.1	1950	179	728	0.18	0.02	0.55	92.1	1483
612	1	0.36	0.11	2015	192	730	0.16	0.01	0.56	80.8	1502
614	1	0.37	0.11	2063	199	732	0.14	0.01	0.56	80.8	1508
616	1	0.38	0.12	2104	212	734	0.13	0.01	0.56	73.3	1513
618	1	0.38	0.12	2141	218	736	0.12	0.01	0.56	73.3	1505
620	1	0.39	0.13	2184	232	738	0.1	0.01	0.56	73.3	1488
622	1	0.4	0.14	2247	244	740	0.09	0.01	0.55	73.3	1467
624	1	0.41	0.14	2303	257	742	0.08	0.01	0.54	73.3	1435
626	1	0.42	0.15	2361	269	744	0.07	0.01	0.52	73.3	1394
628	0.99	0.44	0.15	2454	282	746	0.06	0.01	0.5	73.3	1338
630	0.99	0.45	0.16	2540	301	748	0.06	0.01	0.48	61.9	1281
632	0.99	0.47	0.17	2657	321	750	0.04	0.01	0.45	61.9	1209
634	0.98	0.5	0.18	2803	333	752	0.04	0.01	0.42	61.9	1132
636	0.97	0.52	0.19	2917	352	754	0.03	0.01	0.4	61.9	1056
638	0.97	0.55	0.2	3070	376	756	0.03	0.01	0.37	61.9	983
640	0.96	0.57	0.21	3220	396	758	0.03	0.01	0.34	61.9	903
642	0.95	0.61	0.22	3418	416	760	0.03	0.01	0.31	61.9	839
644	0.95	0.64	0.23	3613	439	762	0.02	0.01	0.28	61.9	738
646	0.95	0.68	0.25	3791	460	764	0.02	0.01	0.25	61.9	677

(Continued)

λ	RQE	A_r	A_{fr}	σ_r $m^2\ mol^{-1}$	σ_{fr} $m^2\ mol^{-1}$
766	0.02	0.01	0.23	61.9	616
768	0.02	0.01	0.2	61.9	539
770	0.01	0.01	0.18	49.8	475
772	0.01	0.01	0.16	49.8	422
774	0.01	0.01	0.14	49.8	367
776	0.01	0.09	0.12	49.8	322
778	0.01	0.09	0.11	49.8	287
780	0.01	0.09	0.09	49.8	248
782	0.01	0.09	0.08	49.8	224
784	0	0.09	0.07	49.8	196
786	0	0.09	0.07	49.8	177
788	0	0.09	0.06	49.8	153
790	0	0.09	0.05	49.8	138
792	0	0.09	0.05	49.8	130
794	0	0.09	0.04	49.8	117
796	0	0.09	0.04	49.8	102
798	0	0.09	0.04	49.8	92.2
800	0	0.09	0.04	49.8	92.2

a From McCree (1972a).
b Phytochrome absorbances and photochemical cross sections determined from purified Rye phytochrome by Sager et al., 1988.

mations of the responses of several pigments and should not be confused with the chlorophyll absorption spectra.

Photomorphogenesis

Photomorphogenesis, in contrast to the energetics associated with direct energy conversion in photosynthesis, defines the effects of radiation on plant development. Several responses of plants, such as germination, flowering, and phototaxis movements, result from the mere presence of light and are not influenced greatly by its intensity, provided certain minimum levels are exceeded.

Studies with monochromatic radiation have demonstrated that most photomorphogenesis reactions are controlled by wavelengths either in the blue region (400 to 500 nm) or in the red-farred regions (600 to 700 nm and 700 to 800 nm). The reactions between 600 and 800 nm have been found controlled or partly mediated by the pigment phytochrome. Narrow-band radiation in the red with the peak at 660 nm and in the farred with a peak at 725 nm can be demonstrated to be the most important wavelengths.

Phytochrome, a bluish photochromic pigment, is the best known photomorphogenic pigment in higher plants. The pigment has two forms, the red-absorbing form (P_r) and the farred-absorbing form (P_{fr}). The P_{fr} form is the active form, although some contradictions exist. The absorption spectra of both forms range from 380 to 700 nm, and the P_{fr} form also absorbs radiation of 700 to 800 nm (Fig. 4). The relative proportion of radiation in the spectrum activating phytochrome (red and farred primarily) to the total irradiance determines the relative cycling rate between the two forms of phytochrome and contributes to the rate or size of the phytochrome response. By determining the ratio of the active state, P_{fr}, to the total phytochrome, P_{tot}, the photomorphogenic responses mediated by phytochrome can be quantified. This ratio, P_{fr}/P_{tot}, is defined as the phytochrome photostationary state, term Φ (phi) and may vary from 0.1, with a radiation source with a high farred spectrum, to 0.75 or 0.89, with a high red spectrum. The phytochrome balance anticipated with different lamp sources can be determined with solutions of pure phyto-

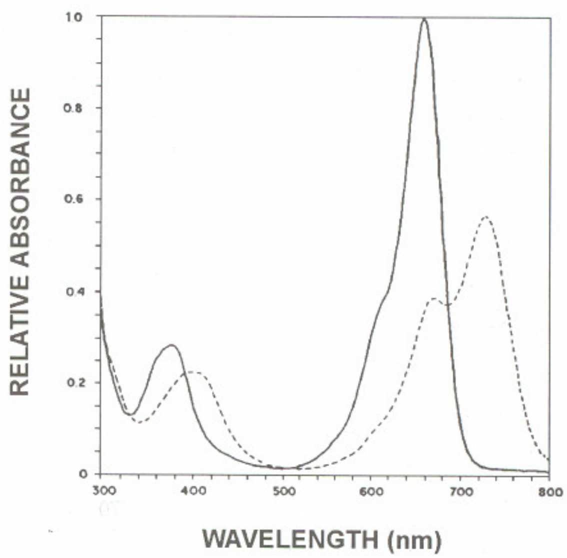


Figure 4. Phytochrome absorption spectra. P_r - red-absorbing form. P_{fr} - farred-absorbing form.

chrome (Sager et al., 1988). Scientists disagree on precise ratios produced by sunlight and different lamps because the determined ratio is dependent on the purification method used to obtain the quality of *in vitro* phytochrome that determines the ratio P_{fr}/P_{tot}. Scientists also disagree on the effect of chlorophyll absorption on the radiation available to phytochrome in the plant (Mohr, 1984). Phytochrome balance can be approximated by multiplying the relative irradiance at each wavelength against the relative absorption of each form of phytochrome (the photochemical cross section) between 300 and 800 nm (Table 3) (Sager et al., 1988; Gardner and Graceffo, 1982) and calculating the phytochrome photoequilibrium (PSS) using the formula:

$$PSS = \left[\sum_{300}^{800} N_\lambda \sigma_{r_\lambda}\right]\left[\sum_{300}^{800} N_\lambda \sigma_{r_\lambda} + \sum_{300}^{800} N_\lambda \sigma_{fr_\lambda}\right]^{-1}$$

Although it would seem that investigators should be very concerned with the balance between red and farred radiation, the most important requirement to meet is that plants have a radiation spectrum that provides an excess of the P_r form of phytochrome during the light period. Some research has shown growth benefits from irradiation that includes incandescent lamps (that would increase the proportion of P_r), but plants have developed normally under radiation sources such as cool white fluorescent and metal halide lamps without addition of incandescent irradiation (Sager et al., 1982; Dijak and Ormrod, 1985; Krizek and Ormrod, 1980). An exception seems to be the need for incandescent irradiation to reduce stem elongation in *Pinus radiata* (Morgan et al., 1983).

Evidence for the existence of blue photoreceptors is overwhelming, but the photoreceptors have not been identified; hence, their effects are less well understood than those of phytochrome (Senger, 1987). These blue/UV-A photoreceptor(s) have been called "cryptochrome" (Mohr, 1984). Action spectra for these effects contain peaks at around 450 nm and 370 nm. These effects include stomatal opening, photomovement, anthocyanin formation, chlorophyll biosynthesis, and many other photomorphogenic processes (Dornemann and Senger, 1984). The critical proportion or absolute blue radiation fluxes has not been determined for these processes. However, Wheeler et al. (1991) have shown that an absolute blue (400 to 500 nm) irradiance requirement exists for controlling elongation in soybeans and that approximately 30 µmol m^{-2} s^{-1} is sufficient. Although less well defined, the blue component of the spectral quality in a plant growth chamber seems as important as the widely acknowledged red/farred component.

Photo control or stimulus of reactions in plants varies over a wide range. A discussion of photostimulus reactions important in growth chamber studies follows.

Germination: Seeds of certain plant species require radiation for germination, particularly native plant species that have not been selected for general crop use. This requirement can be met by planting within the top 5 mm of the soil surface and providing red radiation during germination. This increases the P_{fr} or active phytochrome in the seed or plant tissue.

Hypocotyl: The hypocotyl of species such as beans (*Phaseolus vulgaris*) straighten as the emerging seedling is irradiated.

Flowering: Flowering initiation in most plants does not depend on daylength; in some species, however, critical photoperiods are required. The photoperiodism of different species divides them into two groups, short-day plants and long-day plants. Short-day plants generally show a response (flowering) when the daylength is shorter than the critical photoperiod (commonly ≤12 h), whereas the long-day plants show a response (flowering) when the daylength is longer than the critical photoperiod (commonly >12.5 h). The critical daylength is that photoperiod above or below which the reaction occurs. The distinctions are not very precise because plants change their responses to daylength with age and environmental factors such as temperature and radiation intensity. Some species require a period of long days followed by short days, and some the inverse, to produce the maximum response. The irradiance necessary for some photomorphogenic responses is only the level of a full moon (0.01 $\mu mol\ m^{-2}\ s^{-1}$), but most responses are commonly controlled by levels of 1.0 to 1.5 $\mu mol\ m^{-2}\ s^{-1}$.

Photonastic Movements: Certain movements of plant tissue are initiated by irradiation, including opening and closing of flowers, up and down movement of leaves, and twining of tendrils and stems. Research indicates that short-period (30 minutes to 2 hours) movements of bean leaves and twining of stems require farred radiation. In growth chambers, this requirement can be met with 20% of the input wattage provided by incandescent lamps or farred phosphor fluorescent lamps and 80% by cool white fluorescent or HID lamps. Chambers with HID lamps might have sufficient farred radiation to meet this requirement, but this has not been evaluated.

Stem Elongation: The internodes of plants will be reduced in length if radiation in the blue wavelengths is excessive. Conversely, internodes will elongate if there is an excess of farred. Thus, a balance between blue and farred in the spectrum is required for some plants.

Chloroplast Development: Chlorophyll development in algae as well as certain higher plants requires that a portion of the radiation be in the blue (400 to 500 nm) and near-ultraviolet (380 to 400 nm) wavelengths (Bjorn, 1980). The blue radiation is also required for synthesizing other pigments, such as the carotenoids (Senger, 1987).

Systems and Equipment

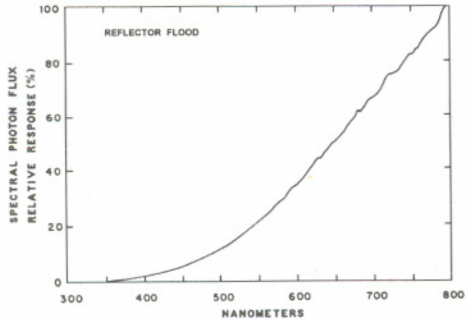
Sources of Radiation

The advantages and disadvantages of different lamps can be shown by comparing their spectral emissions, photosynthetic efficiency, rated life, and output loss as lamps are burned. The spectral emission of each lamp is shown through graphs of relative output per wavelengths between 300 and 800 nm (Fig. 5). The photosynthetic efficiency indicates the photosynthetic photon flux per unit of input electricity. The rated life is the number of hours of operation until 50% of a sample of lamps will be burned out based on 10 hours of operation per start. The output loss as reported by manufacturers is the decrease in lumen output for lamps for the number of hours of operation from first ignition to the "rated life" time.

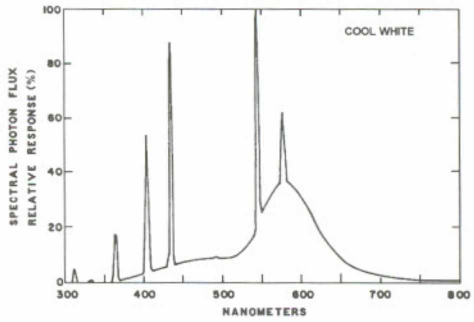
The lamp type should be reported in all controlled environment studies. If different lamp types are being studied in any experiment, then additional information on manufacturer, wattage, and other special characteristics such as coatings or filters should be included.

Incandescent Lamps: Incandescence is the radiation created by a heated body. Therefore, incandescent light is generally blackbody radiation, and the spectrum emitted depends primarily on the temperature of the heated element. Most incandescent lamps use a tungsten filament that operates at a temperature between 2700 and 3050° K (2430 and 2780° C). The spectrum of a reflector flood lamp is shown in Fig. 5a. As voltage is increased, the temperature of the filament is increased. When it attains a temperature above 2600° K, the tungsten emits radiation visible to the human eye, demonstrating that as the temperature increases, the spectrum shifts to include shorter wavelengths of radiation (Fig. 6). Because of this shift in spectrum, the photon flux at these shorter wavelengths increases faster than the total radiated energy. In other words,

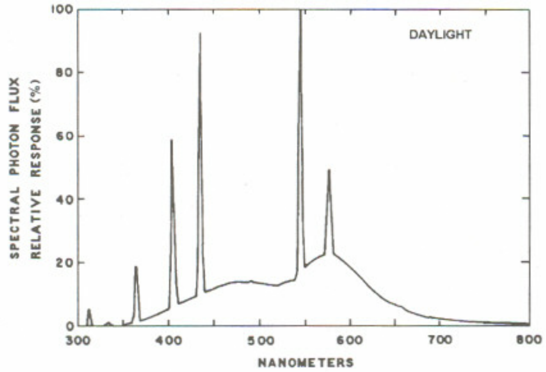
Figure 5. Spectral distribution of radiation sources used in growth chambers:



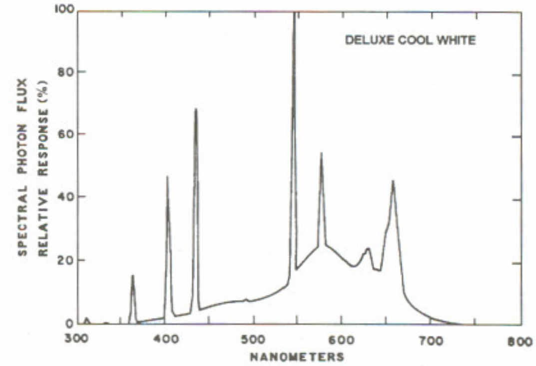
a. Reflector flood incandescent lamp.



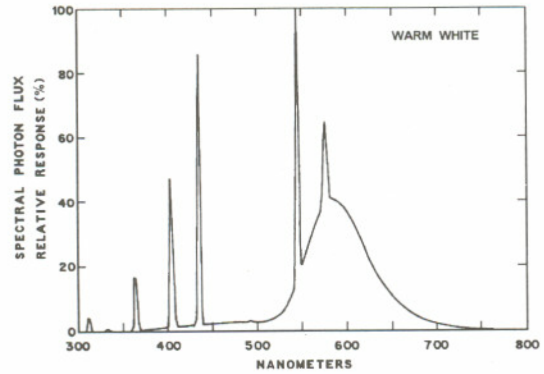
b. Cool white phosphor (CW) fluorescent lamp.



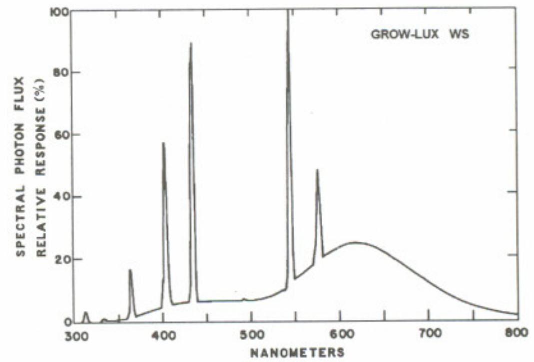
c. Daylight phosphor (D) fluorescent lamp.



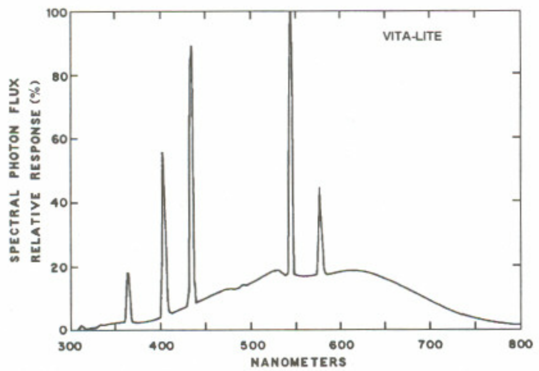
d. Deluxe cool white phosphor (CWX) fluorescent lamp.



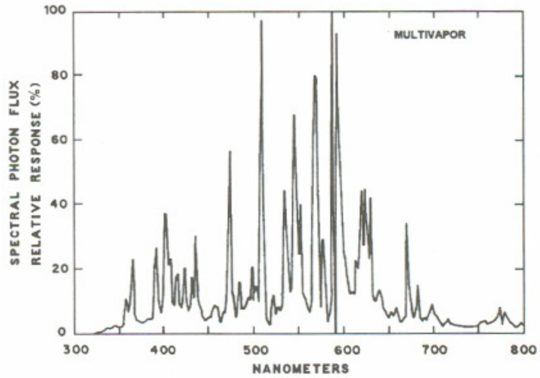
e. Warm white phosphor (WW) fluorescent lamp.



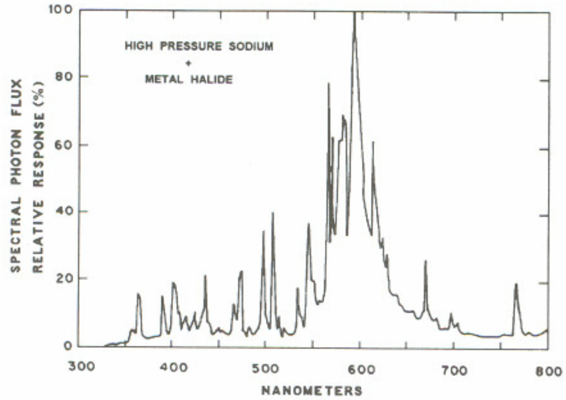
f. Gro-Lux WS phosphor (GRO-WS) fluorescent lamp.



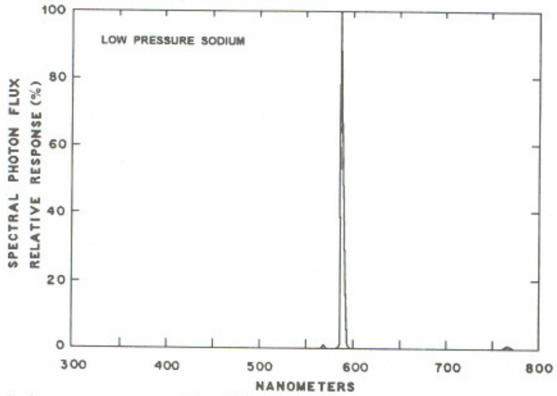
g. Vita-lite phosphor fluorescent lamp.



h. Multivapor phosphor coated HID lamp.



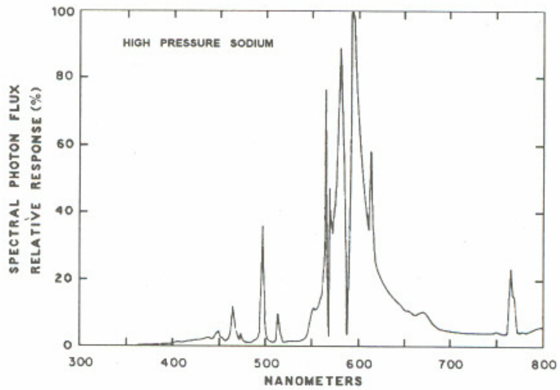
i. Metal halide (MH) HID lamp.



k. Low pressure sodium (LPS) lamp.

the photon efficiency increases. If filaments are operated at a temperature close to the melting point, however, their life is very short; therefore, most tungsten filament lamps operate at cooler temperatures. It is also evident from Fig. 6 and Fig. 5a that most of the energy from incandescent lamps is emitted as infrared radiation. In plant growth chambers, the heat created by infrared radiation must be dissipated and generally is useless to plants. Changing the voltage that ignites an incandescent lamp changes the filament temperature. This technique can be used to regulate irradiance, but spectral shifts will occur (the lower the voltage, the greater the proportion of infrared to visible radiation).

The spectrum of incandescent lamps can be altered by the use of filters, and some bulbs are manufactured with filters built into the envelope. For instance, "daylight" lamps have bluish glass bulbs, which absorb some of the red and yellow portion of the spectrum, and they emit radiation more representative of the natu-



j. High pressure sodium (HPS) HID lamp.

ral solar spectrum. As in all filtered radiation sources, however, the total radiation emitted by these filtered lamps is significantly reduced. Other colored lamps may find specialized use in plant growth chambers. Either clear lamps or "frosted" lamps, having a diffusing filter coating on the envelope, may be used in chambers. This inside "frosting" is applied to incandescent lamps to diffuse the radiation in an effort to eliminate hard shadows. Frosting has very little effect on total output from a lamp, and in our judgment, the benefit gained by partly diffusing the radiation outweighs the disadvantage of obstructed emissions from the surrounding fluorescent lamps. These differences certainly are not large and have little effect on the resultant uniformity or spectral quality in a chamber.

A special type of incandescent lamp is the

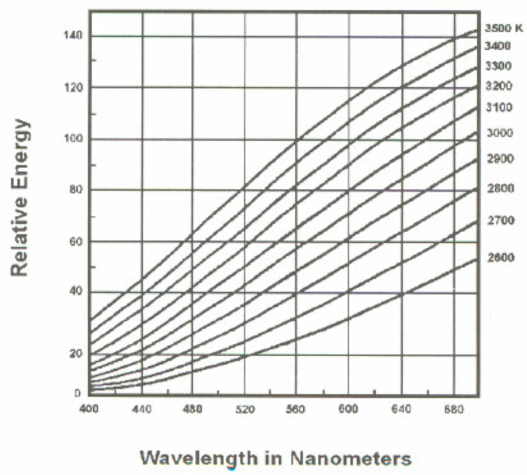


Figure 6. Spectral energy of an incandescent lamp at different filament temperatures.

halogen-filled lamp with a quartz envelope. As in all incandescent lamps, tungsten is boiled off the filament. In regular incandescent lamps, it is deposited on the inside of the lamp and appears as blackening or darkening. In quartz halide lamps, the tungsten combines with the halide to form a gas. When this gas gets near the very hot tungsten filament, it is decomposed, and the tungsten is redeposited on the filament. Thus, the filament is regenerated and theoretically should last forever. Unfortunately, tungsten redeposition is not uniform, and parts of the filament eventually become thin and break. The average life of these lamps is from 2000 to 4000 hours, compared with 700 to 1000 hours for most incandescent lamps.

Incandescent lamps typically show some decrease in radiant output with time of operation. At the end of their expected life, the normal lamp emits 85% of its original light. Some lamps are advertised as longer service or long-life lamps. Longer life is obtained by operating the lamp filament at a lower temperature than normal, such as by operating 130 volt lamps on a 110 or 120 volt line. This method shifts the spectrum, decreases irradiance, causes a lower photon efficiency, and is generally false economy if radiation quantity or quality requirements are not met. These lamps, designed specifically for situations in which changing lamps is very difficult or expensive, have no particular usefulness in growth chambers.

Fluorescent Lamps: Fluorescent lamps have many advantages as a radiation source in growth chambers. When placed close together, they form a continuous, generally uniformly distributed area source of radiation. The output of photosynthetically active radiation is high, and the spectrum generally matches the requirements of plants. Another important reason for their use is that fluorescent lamps are most efficiently operated at about 38°C. Fluorescent lamps are usually constructed from long glass tubes containing mercury vapor at low pressure with a small amount of an inert gas (usually argon). When the electrodes at each end are supplied with the proper voltage, an electric arc is produced through the mercury vapor. Mercury ions are excited in the arc, and when they drop back to the ground state, energy is radiated—maximally in the ultraviolet at 253.7 nm, but emissions at other wavelengths are also radiated. The inner walls of the tube are coated with fluorescent powders (phosphors), which are activated by the emitted radiation and fluoresce at longer wavelengths, primarily in the useful photosynthetic wavelengths. By blending different phosphors, various spectra can be achieved. Many phosphors are available, but not all respond to the primary wavelength energy emitted by the mercury ion. The spectral photon flux distribution for various fluorescent lamps is shown in Figs. 5b through 5g. Deluxe cool white and warm white lamps have a broader spectrum than cool white because of the addition of red phosphor components, although about 30% of the radiation output (compared with standard cool white lamps) is sacrificed. When comparisons were made in controlled studies (Biran and Kofranek, 1976), cool white lamps were the most efficient of the available fluorescent lamps for dry matter production. Most plant growth chambers employ cool white, but some use daylight, warm white, or deluxe cool white depending on the particular desires of the experimenters.

Fluorescent lamps generally are made with three different types of electrical loadings: 400mA; 800mA (also referred to as high output lamp [HO]); and 1500 mA (also referred to as very high output [VHO] or super high output [SHO]). Only the 1500 mA lamps have high enough output for general growth chamber applications. They are rated at approximately 30 watts per foot of tube length. A 4-foot-long lamp

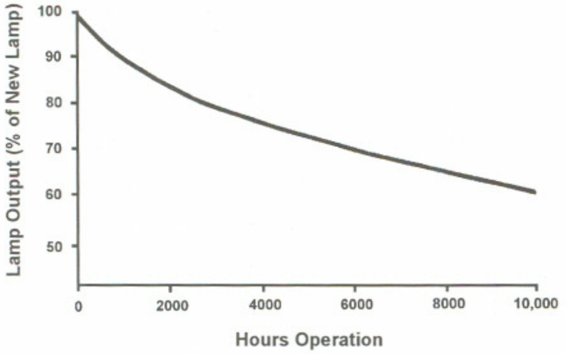


Figure 7. Typical output maintenance for a 1500 mA fluorescent lamp as a function of hours of operation.

produces 110 watts, and an 8-foot lamp produces 215 watts.

Fluorescent lamp life is determined by the emissive coating on the electrodes. During normal operation, this material is slowly evaporated from the filament, and during start-up extra amounts are eroded; thus the frequency of starting and stopping lamps affects lamp life.

Lamp output decreases rapidly during the first 100 hours and then more slowly until the lamp burns out. Figure 7 shows the decrease in irradiance with time the lamp is operated for typical 1500 mA fluorescent lamps. After 6000 hours (1 year at 16 hours per day), the lamp emits 70% or less of its original irradiance. Special types of phosphors used in the lamp may decrease unequally and cause some spectral shift as the lamp ages, but this does not seem to influence plant growth significantly with a "white" phosphor lamp. Lamp life is also influenced by operating line voltage, and either higher or lower voltages than those specified shorten lamp life and reduce efficiency.

Lamp temperature significantly affects the lamp output. Fluorescent lamps are especially sensitive to the ambient temperature because of their construction and the low energy flux per unit area when compared with incandescent or HID lamps. Peak fluorescent lamp output is when the lamp wall is approximately 38°C, as shown in Fig. 8 (the ambient air temperature must be less). The luminaire, or lamp canopy, should be designed to operate near this temperature.

Some fluorescent lamps are designated "plant growth lamps." They have a special phosphor mix designed to match the photosynthetic action spectrum and provide an enhanced blue and red spectrum that plants will use most efficiently. These lamps have specialized trademark names (e.g., Gro-Lux [GTE Sylvania Inc.]). Some studies with these lamps suggest that better growth was obtained than with cool white or warm white lamps, but most studies have not demonstrated any advantage to these lamps, and their output is less than "white" lamps. Also, although "plant growth lamps" can be used successfully to produce healthy plants, the red phosphor (magnesium fluorogermanate) used in these lamps makes them more expensive to manufacture than cool white lamps. Thus, the advantages of Gro-Lux lamps are primarily aesthetic. They produce an interesting purplish color for plants.

High-Intensity Discharge Lamps (HID): High-intensity discharge lamps are discharge devices that excite elements in the arc to emit characteristic elemental line spectra and produce a uniform, but not continuous, spectral distribution. They produce higher irradiances than are obtainable with fluorescent or incandescent lamps. For plant species or particular research studies requiring irradiances greater than 500 μmol $m^{-2}s^{-1}$, these lamps are recommended. The

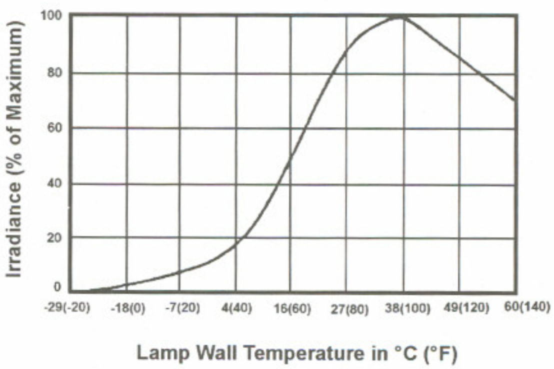


Figure 8. Irradiance from a fluorescent lamp as a function of temperature.

two recommended lamps are metal halide and high pressure sodium lamps. The use of these lamps in growth chambers is increasing because of the demand for higher irradiances. The lamps are essentially point sources; therefore, it is more difficult to obtain a uniform radiation distribution over a growing area with an HID lamp than with fluorescent lamps. HID lamps are produced for luminaires as either base up (BU) or base horizontal (BH). The lamp type must match the type of luminaire. Both types are utilized in growth chambers. Base horizontal lamps are more sensitive to element burnout if jarred or vibrated. Most HID lamps cannot be restarted for nearly 30 minutes after being shut down. Attempts to start immediately after shutdown may shorten the life of the ballast and may short out the starter or the lamp itself.

Metal Halide Lamps (MH): - Radiation from metal halide lamps is produced by arcing electricity through a tube containing vapors of various metal halides in addition to mercury. Halides are usually iodides of thorium, thallium, or sodium. During operation, the metal halides are vaporized and produce the characteristic line spectra. They differ from fluorescent lamps in that the arc length is shorter, temperature is higher, and the vapor pressure of mercury is greater. With increased vapor pressure, the emission lines in the photosynthetically active wavelengths from mercury are intensified, and the ultraviolet wavelengths diminished. The inner quartz arc tube transmits all wavelengths produced, but the outer glass envelope attenuates most wavelengths below 300 nm. The metal halide lamps seem the most useful type of HID lamp for plant research. The emission spectra are almost continuous over the 400 to 700 nm waveband (Fig. 5i). When metal halide lamps are used in critical research studies, it is important to recognize that significant spectral distribution differences occur among lamps and that spectral shifts occur as lamps age; that may produce variable plant growth responses. Unlike the output of fluorescent lamps, metal halide lamp output, as with all HID lamps, is not significantly affected by ambient temperature. The outer envelope acts as a temperature shield, and the temperature of the quartz arc tube remains nearly constant.

Metal halide lamps of 400 watts have an average life of 20,000 hours, whereas 1000-watt lamps have a life of only 12,000 hours (Table 4). The loss of output at 1/2 of the rated life is quite large, nearly 25 percent. The PAR efficiency is high and only slightly less than for high-pressure sodium lamps.

High-Pressure Sodium Lamps (HPS): A high-pressure sodium lamp is particularly useful for plant growth because of its high PAR efficiency (Table 4). In this regard, it is superior to incandescent, fluorescent, and other HID lamps. It also has a long rated life, and its intensity drops off slowly as the lamp ages.

Radiation from sodium lamps is produced by arcing electricity through high concentrations of sodium vapor and a small amount of mercury vapor. This produces an emission concentrated between 550 and 650 nm but low in emission between 400-500 nm (Fig. 5j). Thus plant morphogenic responses, regulated by a blue-absorbing pigment, may not be satisfied if this lamp is used alone. This may be of consequence only at

Table 4. Power characteristics of lamps utilized in plant growth chambers[a].

	Input Power (W)		Ballast
Lamp Type	Lamps	Ballast	Loss (%)
High pressure sodium	400	70	15
	1000	90	8
High pressure metal halide	400	60	13
	1000	80	7
Low pressure sodium	180	50	22
Cool white flourescent	40	6	13
	215	25	10
Incandescent Tungsten	100	None	0
Tungsten - Halogen	1000	None	0

[a] from Campbell et al. (1975)

low irradiance levels, however; because some blue wavelengths are emitted, high irradiance levels may have satisfactory levels of blue (Tibbitts et al., 1983) (Campbell et al., 1975). Thus, it is recommended that HPS lamps be used in conjunction with metal halide, blue phosphor, or cool-white fluorescent lamps. However, if a mixture of lamps is utilized, it is difficult to ensure that all plants receive the same spectral balance of radiation. Also, if multiple lamp types are utilized, the researcher cannot reduce intensities in the growth chamber by turning off some of the lamps or serious spectral imbalances will result.

Mercury Lamps: Radiation from mercury lamps is produced by arcing electricity through mercury vapor much as in fluorescent low-pressure lamps. The clear mercury lamp produces a bluish-white radiation with very little red. Phosphors on the inner surface of these lamps are used to alter the spectrum, as seen in Fig. 5h. These are termed color-improved or mercury phosphor lamps

Most mercury lamps have a long average life (24,000 hours), but as with other electric radiation sources, the output decreases with hours operated. After 12,000 hours, the output is from 70 to 85% of the original, depending on the particular lamp. The PAR efficiency is significantly lower than that of high-pressure sodium lamps, halide lamps, and cool white fluorescent lamps. Thus, they are not recommended for use in chambers unless there is a specific need for UV or blue wavelengths.

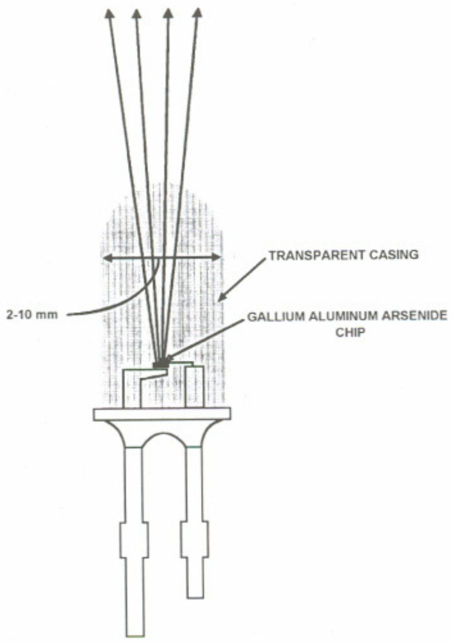
Low-Pressure Sodium Lamps (LPS): Elemental sodium is electrically excited in these LPS lamps much the same as in the high-pressure sodium lamps, but concentrations are less and no mercury vapor is present. Thus, only the primary emission spectrum at 589 nm is present in the PAR region (Fig. 5k). The irradiance level is usually not great enough to be as useful as fluorescent or HID lamps in growth chambers. Also, the total lack of 400-500 nm radiation has resulted in significant morphogenic changes, and even lack of chlorophyll formation in certain species.

Self-Ballasted Mercury Lamps: Most major lamp companies supply self-ballasted mercury lamps that can be utilized in an a-c line without the need of a ballast. The lamps provide radiation from both a tungsten filament and mercury arc emission. These lamps are not recommended over fluorescent or HID lamps for use in growth chambers because they emit a large quantity of radiation in wavelengths longer than 700 nm. Long-wave radiation is not photosynthetically active and thus is an additional heat load to the chamber.

Xenon Lamps: Xenon lamps have the potential of providing radiation for plants that most nearly duplicates the solar spectrum and most nearly approximates the irradiance level of sunlight. Unfortunately, they are expensive, generate ozone (which is toxic to plants), and generate large quantities of infrared radiation that increases the cooling requirements in the chamber. Thus, they have only limited use in a growth chamber. They are used extensively in photobiology to produce high-irradiance narrow spectra when significant filter attenuation of long-wave radiation is provided.

Light-Emitting Diodes (LEDs): Light-emitting diodes have usefulness for plant irradiation because certain diodes have a spectral output (620 to 680 nm with maximum at 650 nm) that has maximum photon effectiveness for photosynthesis. The radiation from these devices is directed outward at a narrow angle so no reflector is required. The construction and spectrum of a red gallium aluminum arsenide LED are shown in Figs. 9a and 9b, respectively. Arrays have been constructed by Bula et al. (1991) with individual devices 1.5 cm apart. These arrays have produced irradiances of 700 $\mu mol\ m^{-2}\ s^{-1}$ a few centimeters below the devices. Lettuce seedlings developed chlorophyll but produced greatly elongated hypocotyls and narrow cotyledons under these LEDs, but lettuce growth was essentially normal when the LEDs were combined with 30 μmol m^{-2} s^{-1} of blue photons from blue fluorescent lamps (Hoenecke et al., 1992). At publication of this volume, high irradiance blue LEDs are available; however, few data are available in their use for plant irradiation. The LEDs can be pulsed very rapidly with on-off cycles (in microseconds) and thereby provide the potential of cycling these lamps very rapidly to increase irradiation efficiency significantly. However, cycling at 1.5, 7.5, or 15.0 microseconds has resulted in no additional efficiency (Tennessen et al., 1995). A limitation to use of LEDs is that PPF efficiency is less than that of HID lamps, but seemingly better than cool white fluorescent lamps. With improvement in reflective optics within the device, efficiency may be improved.

Microwave Lamps: Electrodeless bulbs filled with a variety of elemental components, such as Li, S, Hg, or a combination of elements have been developed for visible lighting since the 1930s. External excitation of these electrodeless bulbs included electromagnetic fields and microwaves. Recently a mercury-free, low infrared, efficient lamp using benign sulfur-based fill has been developed for plant growth applications (Dolan et al., 1992). This microwave source has achieved conversion efficiencies exceeding HPS lamps, but the efficiency of the microwave source, a magnetron, has not been improved, so the overall efficiency is less than that of HID lamps. The unique attributes of the lamp are its small size (2.5 to 5 cm, nearly approximating a point source for luminaire design), its ability to meet optimal spectral requirements for plant growth, and its low near-infrared emissions. Further work is necessary to achieve optimal lamp fill materials and excitation configurations. Researchers are presently using these microwave sources for broad spectrum plant growth experiments.



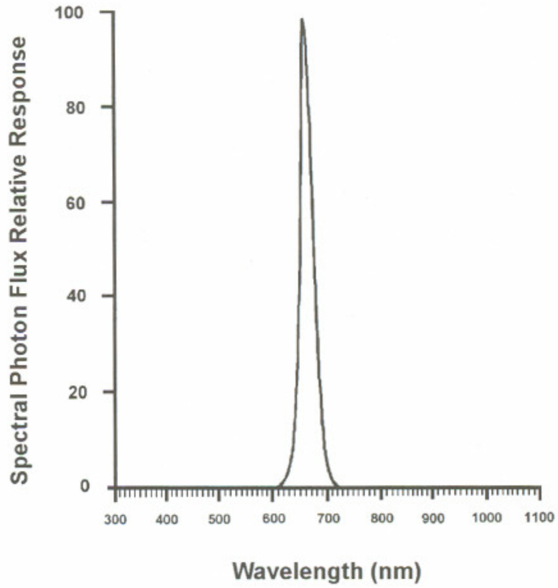


Figure 9A. Construction of gallium aluminum arsinide LED.

9B. Spectral photon flux of the LED in 9A.

Ballasts

An important part of all fluorescent and high-intensity discharge lamps is the ballast. It serves as a transformer to provide sufficient voltage to start and operate the lamp. After the lamp is started, the gas in the tube ionizes and becomes an electrical conductor. Resistance, therefore, decreases, and unless regulated by the ballast, the current would increase and burn out the lamp. This regulation requires power in addition to the wattage required for operation of lamps. The power required is between 10 and 25% of the lamp wattage, with the percentage varying with lamp type and the wattage of the lamps (Table 4). The ballasts warm and radiate heat; thus, they should be located where this heat can be dissipated readily. Generally ballasts are mounted to the outside of the plant growing area to reduce cooling requirements within the growing area, but they may also be used to supply heat to the enclosure or building. The high voltage required to start HID sodium lamps, however, makes it impractical to extend voltage wires more than 10 or 20 meters between the lamps and ballasts. This is not a limitation with HID metal halide lamps, for which the voltage is much lower and wires can be extended tens of meters if needed.

Ballasts are sized and thus are generally specific to a type of lamp and the wattage of the lamps being operated. However, fluorescent lamps of the same wattage, i.e., cool white, warm white, and Gro-Lux, can be operated from the same ballasts. Also, it is now possible to obtain special HID metal halide lamps that can be used in HPS fixtures and ballasts. These are priced significantly higher than standard MH lamps and are less efficient.

Lamp Reflectors

A lamp reflector is a significant factor in that it directs the radiant energy from the lamps to the plants. Without a reflector, less than 50% of the radiation from a lamp would be received by plants. Commonly, fluorescent lamps are mounted with a flat reflective surface above the lamps that directs radiation partly through the spaces between the lamps, but a significant portion of radiation is reflected back into the lamps and is lost. In contrast, HID lamps are mounted with individual reflectors surrounding each lamp and usually are designed so most of the upward-directed radiation is reflected downward to the plants. As a consequence, chambers with HID lamps have greater reflector efficiency than chambers with fluorescent lamps, and significantly less wattage is required for an equal amount of irradiance at the plant level.

Reflectors have been constructed with fluted sides or smooth surfaces. The fluted sides are intended to provide better dispersion of radiation. Fluted reflectors, however, seem to have no significant advantage over smooth-surface reflectors.

Certain reflectors have fittings that permit adjustment of the lamp position so that maximum uniformity can be obtained at a desired distance below the lamp. Care should be taken in setting these lamps so that necessary uniformity is maintained as plants increase in height during an experiment.

Lamp Canopy Barriers

Barriers are used between the lamp canopy and plant growing area to reduce cooling requirements in the plant growing area. Usually the lamp area is maintained with a separate air exchange system that conducts heat from the lamps and from the warmer barrier. This lamp area air should be temperature controlled to maintain a uniform air temperature in the lamp area. This is particularly critical for fluorescent lamps because their output is very temperature dependent. Changes in temperature can cause irradiance to increase or decrease 1 to 3% per degree Celcius. Chambers without barriers may have significant variations in fluorescent lamp output when experiments are run at widely different temperatures. For instance, the output of fluorescent lamps in an experiment at 15°C may be only 70% of the lamp output for a similar experiment conducted at 25°C. Similarly, variations can occur when a barrier is used if the temperature of the room air used to cool the lamps varies greatly at different times of the day or at different seasons. Chambers that have separate temperature controlled lamp compartments may also suffer from lack of temporal uniformity. Because the heat generated is significant and the air volume is usually small, temperature cycling in the lamp compartment often is sufficient to produce significant cycling in irradiance. Each user, therefore, must evaluate his own chamber to learn what conditions exist that may reduce the uniformity of the radiation in the chamber.

Temperature control around lamps is less important with HID lamps because they operate at very high temperatures, but temperature fluctuations will influence lamp output through effects on the output of HID ballasts if these are located in the lamp canopy area. Also, the temperature of the canopy area will control the temperature of the barrier material and thus control the blackbody radiation of the lower surface of the barrier radiation into the plant growth area, which increases or decreases 5W m^{-2} for each degree Celsius (around 20°C). The barrier serves a significant role in absorbing long-wave radiation and thus reducing the direct radiational heating of plant leaves and soil in the chamber. This role of barriers can be served by hanging sheets of transparent material just under lamps even though they do not make a tight barrier. The long-wave radiation from HID lamps was reduced 25% by the 1/4 in thick sheets of acrylic material 30 cm under the lamps (Wheeler and Tibbitts, personal communication). The Biotron at Kyushu, Japan, has 50-cm-diameter discs of acrylic material supported by thin rods under each HID lamp.

Reflective Surfaces

Chamber manufacturers use a variety of materials for walls and ceilings. Specular materials such as mirrored aluminum film on mylar, specular aluminum sheets, and stainless steel sheets, along with reflective white painted surfaces, have been used extensively. Mirrored glass is utilized in some chambers. A collection of reflectance curves for different materials has been presented by Hollaender (1956) and by Bickford and Dunn (1972). Tests of various materials in actual plant growth chambers were conducted by the Bioclimatic Laboratory Development Project at Cornell University in 1961 (Davis and Dimock). Tests indicated rather small differences among different materials. Mirrored surfaces have the greatest reflectance but reflect the lamp image and thus give less uniformity than specular or painted surfaces. Enamels containing magnesium oxide paint have the highest reflectance with the least dependence on spectrum. Their data showed that specular ceilings and walls gave the highest light values in the chambers. The difference between specular and diffuse ceilings decreased as the lamps were moved closer together. White, diffuse walls gave a more uniform radiation distribution in the chamber. When repairing or replacing reflective surfaces, several other factors should be considered. Painted surfaces can be cleaned quite effectively, whereas other surfaces tend to scratch, and glass and mirrors lose reflectancy. Also, replacement of mylar films is quite difficult because it is hard to remove the old film. Repainting of surfaces can be done easily, but the enamel paints contain toxic solvents that can damage plants growing in nearby chambers; thus paints require a period of several days to weeks after application to permit complete drying and toxic outgassing.

Lamp Spacing

Fluorescent lamps are spaced as closely together as possible to obtain maximum intensities in chambers. Double layers of fluorescent lamps will produce some increase in intensity, but the increase is not as much as might be expected because the lower layer causes significant shading and capture of radiation from the upper layer. HID lamps need to be spaced at intervals to obtain as uniform an irradiance as possible. The use of low-wattage lamps increases uniformity over the use of a smaller number of high-wattage lamps providing the same total wattage. The lamps or fixture in some lighting units can be adjusted up or down to affect their distribution pattern. Also, reflector design, as discussed in a preceding section, will affect irradiance distribution. Under HID lamps, the horizontal pattern of distribution can vary significantly at different heights because the reflectance angle of luminaires results in the concentration of irradiance at specific distances below the lamp. Thus distribution patterns should be determined at the different heights at which the plants will grow.

Measurement

The radiation environment must be defined by the quantity and the quality (wavelength) of the radiation impinging upon the plants. Additionally, an important parameter to define is the direction of the radiation, but little emphasis has been placed on defining how this might be accomplished in plant growth facilities. Measurements are commonly made with the receiver plane of the sensor aligned perpendicular to the radiation source. It is assumed that the leaves act as flat receiver surfaces aligned perpendicular to the source. This is not actually the case, however; sensors are constructed with cosine receiver filters that correct for reflectance of radiation that impinges on the detector at angles other than normal to the receiver. This correction follows the Lambert cosine law so that when radiation strikes a detector at an angle, the amount of radiant flux absorbed is corrected (reduced) to equal the value that would occur if the detector were perpendicular to the rays, multiplied by the cosine of the angle. This filtering is called cosine correction, and the diffusing cover is called a cosine correcting filter.

In certain experiments, measurements are made with spherical sensors that monitor radiation impinging upon the plant from all directions. These measurements are useful for algae floating in water and for plants being irradiated from within the plant canopy or with nonplanar lamp arrays.

Sensors

Two types of sensors, photoelectric and thermoelectric, are in common use in monitoring the radiation in plant-growing environments.

Photoelectric: The most frequently used sensor is a photodiode (photovoltaic) sensor, used in most PAR sensors, spectroradiometers, and photometers. The negative electrode (cathode) on top of the sensor is covered with a thin transparent film, and the positive electrode (anode) is on the bottom. When exposed to radiation in its sensitive range, an electromotive force is generated proportional to the irradiance. These sensors are of particular usefulness because of their thermal insensitivity, ruggedness, and light weight. They do, however, develop a "dark" current that must be removed with appropriate circuitry. Silicon is the commonly used semiconductor in PAR sensors and spectrophotometers. It has a spectral sensitivity for wavelengths between 400 and 1100 nm and is therefore filtered

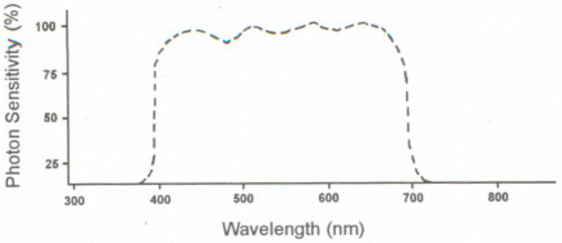


Figure 10. Relative photon sensitivity of a commercial PAR sensor (courtesy LiCor Inc., Lincoln, NE)

in PAR sensors to obtain the desired wavebands of sensitivity and desired balance in sensitivity for the different wavebands. A typical filtered silicon sensor used with a PAR meter is shown in Fig. 10. Silicon sensors also are utilized for the production of infrared sensors that commonly respond to radiation between 700 and 800 nm. These sensors should only be used to monitor relative levels of farred irradiation and should not be used to predict phytochrome activity of different lamps. This caution is given because the farred-absorbing form of phytochrome (P_{fr}) exhibits considerable absorption and activity at wavelengths other than the farred; thus, significant errors in phytochrome response may be obtained if this type of sensor is used.

Selenium is a commonly used semiconductor in photometers (light meters) because it is cheap and has a sensitivity similar to the human eye. It is not useful as a PAR meter, however, because of its low sensitivity below 450 nm and above 650 nm.

Another photoelectric detector is a photomultiplier tube (photoemissive), which is a gas-filled, evacuated tube containing photosensitive cathodes. When radiation is absorbed by the cathode, electrons are emitted. An electric potential causes these electrons to migrate to the anode and produce a current proportional to the radiation level. The sensitivity of the cathode is wavelength dependent, as with photovoltaic devices, but tends to fatigue rapidly and thus require frequent calibration for accurate monitoring. Photomultiplier tubes are utilized in some spectroradiometers and are required in ultraviolet spectroradiometers instead of silicon sensors to obtain needed sensitivity at less than 350 nm.

Thermoelectric. These detectors utilize a blackbody that absorbs radiation incident upon it and measures the resultant heating. The wavelength range of any thermodetector is limited by the cover, such as plastic or glass, which is placed over the sensor to avoid variable convection (air currents) across the sensor surface. The plastic or glass has specific transmission characteristics:

Quartz glass	280 nm to 2800 nm
Polyethylene	320 nm to 50,000 nm
Silicon	1100 nm to 70,000 nm

To obtain an accurate measurement of total energy radiating from a lamp, it is necessary to use a thermodetector covered with polyethylene rather than quartz glass. Scientists have shown that the energy from lamps can be underestimated by 25% if only a quartz glass covered radiometer is used (Bubenheim et al., 1988; McCree, 1984; Tibbitts and Sager, 1986). This is in contrast to use of these instruments in field environments, where glass-covered thermodetectors accurately monitor emissions from the sun because the atmosphere absorbs most of the solar radiation in wavelengths greater than 2,800 nm.

Instruments with polyethylene domes are used by meteorologists to measure the balance between incoming and outgoing radiation. These instruments are called net radiometers. Net radiometers can be used in chambers for monitoring the radiation from lamps, but they must be modified so that the lower surface of the radiometer is enclosed with an opaque sphere; thus, they are commonly called modified net radiometers.

Calibration

To assure the quality of the measurements of the radiation environment, specific procedures should be followed for calibration (Tibbitts and Sager, 1987). Calibration of radiation sensors is critical for reducing error in measurements. Calibration should be scheduled on a regular basis. Broad-band sensors, such as PAR sensors, should be calibrated biannually, or semiannually if used continuously. Two methods of calibration are commonly used. Simple comparison of an on-line sensor with a reference sensor is usually sufficient for on-line control or monitoring. The reference sensor is maintained only for such comparisons and is calibrated with a standard lamp traceable to the National Institute of Testing and Standards (NITS). The on-line sensors should be calibrated to the reference sensor in a growth chamber under the spectral and spatial conditions in which the on-line sensor will be used.

The second and more rigorous method is to calibrate the on-line sensor directly with a standard lamp traceable to the NITS. Standard lamps, however, require a darkened, light-tight room, an optical bench or other mounting hardware, and a regulated power supply. Standard lamps have a limited life, are fragile, and are expensive. If you do not have a standard lamp available for calibration in your laboratory, you can usually obtain this calibration from the manufacturer or a separate company that provides calibration services. The use of standard lamps or reference sensors at your location is recommended over shipping all the instruments back to manufacturers or shipping instruments to a calibration service because instruments may be damaged during the return after calibration.

Experiments

When radiation is the central theme, experimental design will dictate what, when, and how to measure radiation. The following suggestions apply only when radiation is not the objective of the study and environmental conditions are being measured to document the radiation environment of the experiment.

At Start: The photosynthetic photon flux (PPF) should be monitored with a PAR meter. This should be undertaken in the chamber across a grid covering the plant-growing area at points no more than 0.5 m apart. To effectively monitor variations in irradiance across the chamber, the grid should encompass measurements at closer intervals when using HID, or other point source lamps. The measurements should be taken at the top of the pot or at the top of plants being placed in the chamber. The grid measurements provide a basis for blocking of treatments to ensure balanced lighting for the plants in the experiment.

To obtain the desired photon flux level, radiation intensity can be adjusted by using one or more of the procedures discussed in the regulation section of this chapter. It is recommended that the radiation level be set at 5% above the desired level at the start of the experiment; when the level decreases with lamp aging to 5% below the desired level, adjustment should again be made back to 5% above the desired level. In this way, the average level over the experimental period will be the desired level for the experiment.

A spectroradiometer measurement taken in the center of the chamber is recommended. This should be taken for the waveband of 300 nm to 800 nm. This measurement is strongly encouraged if photomorphogenic effects on plants are being studied.

A measurement of total radiation by using a modified net radiometer at the center of the chamber is also encouraged. These instruments (i.e., from Radiation Energy Balance Systems, Bothell, Wash.) are not generally available to plant scientists. An alternative measurement is the use of two Eppley radiometers to measure total radiation in segments. By using a precision spectral pyranometer (PSP) and a pyrgeometer (PIR), the total radiation is measured in two segments, 265 nm to 2800 nm and 2800 nm to 70,000 nm. These measurements are particularly important in experiments in which two different irradiance levels are being compared because the total radiant energy in the two experiments may be quite different. The different total radiation levels may produce different leaf and soil temperatures even though equal PAR levels and similar air temperature levels are maintained in each chamber.

Weekly: The photosynthetic flux should be monitored each week at the top of the plant canopy at the same locations monitored in setting up the experiment. The average difference in these readings can be used as the basis for evaluating the temporal intensity changes and at the appropriate time to adjust radiation intensity. The first readings should be taken at the time of planting and at weekly intervals thereafter. Wait at least 30 minutes, and preferably longer, after lamps are turned on to allow stabilizing of lamp output before taking readings. The photosynthetic flux taken from the four locations in the weekly readings as corrected should be averaged and used for reporting in publications (see Chapter 15 in this handbook).

Gradients in Chambers

Significant horizontal and vertical gradients exist in chambers. These vary in different chambers with chamber size and shape and with type of lamps and shape of the luminaire.

A vertical gradient is present in all chambers, with radiation decreasing with distance from lamps. It decreases more rapidly with distance in small chambers than in large rooms because small chambers respond as if they were a point source of radiation and large rooms respond as if they were area sources of radiation. The irradiance of a point source at any distance from the source is inversely proportional to the square of the distance from the source. This relationship is known as the "inverse square law." An array of fluorescent lamps in a chamber, however, particularly an array of long fluorescent lamps, provides an area source rather than a point source. Such an area source approaches a linear inverse relationship in which the irradiance is inversely proportional to only the distance and not the square of the distance from the source. Irradiance may, however, vary significantly from either of these source-distance relationships in different chambers because of the type of reflectors and arrangement of lamps, but it will be between these two estimates.

The horizontal gradients in chambers are also significant. In chambers with fluorescent lamps, irradiance is high in the center of the chamber

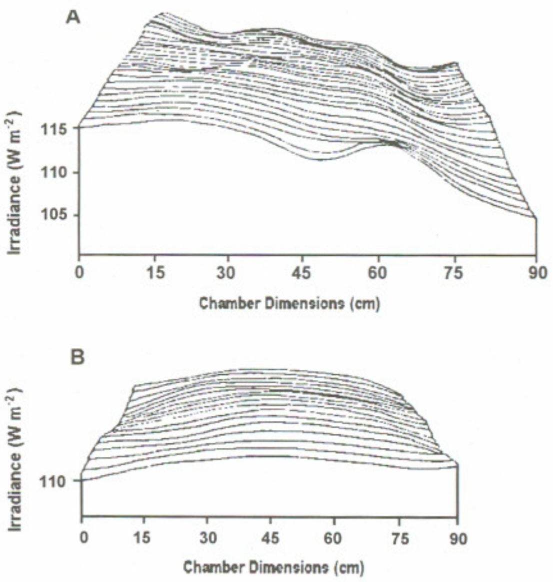


Figure 11. Photosynthetically active irradiance (W m^{-2}, 400 to 700 nm) surface viewed from the door side of two growth chambers. These surfaces were generated from data taken at 15 cm centers. (A) Differences in reflectance from side walls in this 1.5 m^2 chamber created the gradient from left to right. (B) More uniform distribution occurred in another commercially available, 1.1 m^2 growth chamber.

and decreases toward each wall. Figure 11 shows the equal irradiance patterns in two of the author's chambers, an asymmetric and a symmetric pattern. Irradiance variations tend to be the dominant environmental variations in chambers and should be used as the primary basis for experimental blocking. Because the variation radiates from a center maximum with a symmetric pattern or from an end with an asymmetrical pattern, experimental blocking should be based on concentric rings rather than square or linear arrangements.

When making measurements, it is important to remember that irradiance varies with the lamp temperature. This can be demonstrated by recording the energy or photon flux in the center of the chamber from the start of a photoperiod for at least two hours. These measurements will reveal the changes that occur during warm-up and will allow evaluation of cycling coincident with temperature fluctuation in the lamp canopy. The horizontal gradients can be determined by positioning empty pots or some other marker on the rack or bench in a regular grid; the number depends on the experimental design and the chamber size. Place sensors on each pot and record the photon flux level. If intense cycling occurs as a result of temperature changes, it may be necessary to allow the cooling system to make one complete cycle at each measuring station. Then select a common point at the top, bottom, or median of the fluctuation for the intensity value. Plots of the variation across the chamber will be useful for the design and evaluation of experiments. A decrease in energy level will be found close to the wall; plants, therefore, are commonly maintained no closer than 15 to 30 cm from any wall surface. In chambers with HID lamps, levels will not decrease significantly from the center to the walls of the room, but there can be significant variations across the growing surface. The variations with HID lamps increase as fewer HID lamps are used. For example, a chamber with 4 - 1000W HIDs will have greater variation than a chamber with equal lamp wattage from 10 - 400W HID lamps.

Spectrum

The radiation sources should provide necessary wavelengths to stimulate all photosensitive reactions in plants. It is not necessary to reproduce the natural solar spectrum to have plants respond with normal development. The use of only "white" spectrum lamps, such as a cool white fluorescent lamps or metal halide lamps, provides normal growth in most species.

High-pressure sodium (HPS) lamps will produce normal growth only if the intensity is high enough. High-pressure sodium lamps have insufficient blue wavelength emissions to satisfy the blue-absorbing pigment requirements of certain plants at low irradiances. This requirement for blue wavelength becomes less critical as the intensity of high pressure HPS lamps increases. A supplementation of 5 to 30% of the total lamp wattage with metal halide or cool white fluorescent in combination with HPS lamps will provide the required blue wavelengths.

Low-pressure sodium lamps (LPS), if used alone, do not provide for normal growth of plants and must be supplemented with blue wavelengths. Certain plant species, as soybeans (Wheeler et al., 1991) and *Pinus radiata* (Morgan et al., 1983), require blue or farred supplementation. Fluorescent, metal halide, or incandescent irradiation, providing at least 5 to 30% of the input wattage, is required for normal growth of these plants. Thus, it is recommended that a portion of the total irradiance in growth chambers with LPS lamps be provided from other lamps to have an effective irradiation spectrum for all plants.

Duration

The duration of the radiation (photoperiod) is the most easily controlled variable of the radiation environment. Generally, lamps are automatically and abruptly turned on or off with a timeclock. Stepwise changes in irradiance are achieved in some chambers by turning groups of lamps on or off in sequence to simulate dawn and dusk or change the spectral quality. Examination of the literature reveals no plant responses dependent on a gradual change in irradiance at the beginning or end of the photoperiod; therefore, stepwise changes are not necessary unless required for better temperature and/or humidity control. Changes in spectral quality must be carefully controlled, and a much more sophisticated control than stepwise changes is recommended.

Irradiance

The maintenance of desired radiation levels or irradiance in chambers is a major variable in plant research and is a primary difficulty in duplicating growth in successive experiments or in two different chambers. The principal reason is that the output of photosynthetic radiation from lamps is constantly decreasing. Primarily this decrease results from the fact that with use (cycles and total time) the output of a lamp decreases. As a consequence, it is commonly recommended that after every 3 months of operation, 1/3 of the lamps should be changed. The replacement of 1/3 of the lamps, however, can produce as much as a 20% increase in photosynthetic irradiance, which then slowly decreases until the next change in lamps. This varying light level will result in significant variations in the growth rate of plants over the experimental period. For many research studies, irradiance levels must be maintained with no more than a +5% variation in level. This becomes a necessity when two or more chambers are being utilized for an experiment comparing levels of a factor such as irradiance, spectral quality, temperature, or humidity. Thus, rather than changing lamps on a schedule, we recommend using one or more of the following procedures to maintain irradiance levels in a chamber or to obtain comparable levels in separate chambers:

1) Adjust the plant growing level.
2) Change the number of lamps used.
3) Introduce shading material.
4) Dim the lamps.

Lamps eventually degrade to an irradiance below the desired level. Commonly, all the lamps are replaced at this time and the irradiance is adjusted again to the desired level by using the procedures listed.

Many small chambers have systems that permit raising or lowering the plant-support rack as needed. This is a simple and rapid way of setting or balancing irradiance levels. Movement of the plant rack, however, may have an effect on airflow patterns over the plants and the containers; thus, if two chambers have quite different rack heights, make certain that soil temperatures and airflow patterns are not significantly different.

The number of lamps being used can be altered to change irradiance effectively in chambers fitted with fluorescent lamps, but not readily with HID lamps. Fluorescent lamps are usually wired in pairs, a pair for each ballast, and one of each pair mounted in balanced fashion on each half of the lamp bank to maintain symmetry. Thus, separate pairs of lamps can be de-energized or energized to alter irradiance intensity without seriously affecting irradiance uniformity in the chamber. The operation is simplified if a switch is installed across wires leading to each ballast. A less significant change in intensity can be obtained by replacing used lamps with new lamps or vice versa. When replacing lamps, however, make certain that both lamps of a pair are replaced to avoid rapid loss in life of new lamps. In chambers with HID lamps, it usually is not possible to turn on or off individual lamps because this results in unacceptable non-uniformity over the plant growing area.

Shading is used in chambers where other procedures are not available and also to make small changes to carefully balance levels within each chamber or between two chambers. Various types of screening, plastic shade materials, or white loosely woven cloth can be utilized. Screening can be placed on the lamp barrier or can be strung across the chamber just under the lamp barrier with wires or string. Screening is usually cut and shaped so that as the irradiance decreases, it can be moved to equalize irradiance and improve irradiance uniformity within each chamber. The shading should be mounted high enough so that it does not interfere with cultural practices or the air circulation stream in the chamber.

There have been many attempts to develop dimming devices for different lamps. It can be done effectively with HID lamps, incandescent lamps, and fluorescent lamps, but the dimming range is less with fluorescent lamps. When lamps are dimmed, spectral shifts may occur that have an impact on plant responses or plant quality. The spectral shifts are particularly significant when HID and incandescent lamps are used. The shift associated with reducing voltage to dim incandescent lamps is seen in Fig. 6. HID lamp dimmers are available that involve triac circuits. The cost of these dimming ballasts is several times the cost of a standard ballast. Dimmers for HID lamps can reduce irradiation intensity down to about 70% of the full irradiance output without any significant spectral shift, but further dimming will cause spectral shifts. Whenever lamps are turned off and restarted, they must be energized to full wattage before dimming again. Thus automatic control of daily light/dark periods is greatly complicated by using dimming ballasts on HID lamps.

Safety

The radiation systems in a growth chamber make up a major portion of the electrical, mechanical, and materials dangers in the operation of growth chambers. Electrical shock from the power distribution wiring, as well as from the actual fixtures, is a major cause of this hazard. The overhead position of lamps, luminaires, barriers, and attaching hardware significantly loads the structure and poses a danger from falling objects. Toxic elements and rare earths (such as mercury and phosphors in fluorescent lamps), lamp envelope temperature, and potential breakage of the envelope and barrier combine to impose handling and containment hazards. The high intensities of visible radiation are a hazard to eyes, and darkened glasses are recommended. This hazard becomes even more serious when working under lamps with high UV levels, as with mercury HIDs, most fluorescent lamps and metal halide lamps. Darkened UV-absorbing glasses should be worn. These safety considerations are not minor and periodically must be brought to the attention of users and operators of growth chamber facilities. As with any energy-emitting system, the source must be safely energized and the radiation shielded or attenuated to reduce the risk of overexposure.

Glossary

Bolometer - A radiometer utilizing the changing resistance of a sensor with changing temperature to determine the energy of radiation.

Cosine correction - A diffusing cover on a radiation sensor that corrects the radiation arriving at the sensor proportional to the cosine of the angle of incidence. The receiving surface is assumed to be planar.

Energy - The quantified ability to do work.

Farred - Radiation between 700 and 800 nm.

Flow - The transfer of mass or energy per unit time.

Fluence - Term describing the quantity of radiation received perpendicularly onto a point or onto a sphere from all spherical angles.

Flux - Quantity (of radiation) per unit time passing through a horizontal surface.

Infrared - Radiation longer than 800 nm, sometimes divided into near infrared (800 to 3000 nm) and thermal infrared (3000 nm and greater). To define particular wavebands as "thermal" radiation is misleading because all radiation produces temperature increases when absorbed.

Irradiance - Energy flux or energy flow rate per unit plane surface area.

Irradiation - Radiation impinging on, or received at, a surface measured as irradiance or photon flux.

Light - Visually evaluated radiant energy, with wavelengths ranging between 380 and 720 nm, based on the sensitivity of the human eye.

Modified net radiometer - A radiometer designed to measure "total" (300 to 50,000 nm) radiation on a horizontal surface. The device requires careful correction for the temperature of the growth chamber and of the lower enclosed surface so that accurate determination of lamp radiation can be made. (See Net radiometer).

Near infrared - Infrared radiation between 700 and 3000 nm or 800 and 3000 nm, as defined by specific scientists. Used to distinguish from radiation longer than 3000 nm, which is often termed thermal infrared or thermal radiation. (See further explanation under Infrared.)

Net radiometer - A radiometer designed to measure the difference between the "total" (300 - 50,000 nm or longer) radiation impinging upon the upper surface of the instrument and that received on the lower surface of the instrument. It is used to determine the net balance of radiation on a surface and is of little use in growth chamber research. (See Modified net radiometer.)

PAR (Photosynthetically Active Radiation) - A general term used to describe radiation in wavelengths useful for photosynthesis of plants. Generally accepted to be wavelengths between 400 and 700 nm, although sometimes defined to include wavelengths as short as 350 nm and as long as 800 nm. The specific quantity of radiation should be reported as photons (see PPF and PPFD) or energy (see PI).

Photon - A packet of the smallest unit of radiation.

PI (Photosynthetic Irradiance) - The photosynthetic energy received on a horizontal surface and cosine corrected for angle of interception. Generally accepted to include wavelengths between 400 and 700 nm, but sometimes defined to include wavelengths as short as 350 nm and as long as 800 nm. The radiation units are Watts and are commonly reported as $W\ m^{-2}$.

PMR (Photomorphogenic Radiation) - Radiation with wavelengths approximately ranging between 300 and 800 nm contributing to photomorphogenic responses (i.e., flowering, reproduction, elongation, dormancy) in relation to the radiation in several discrete spectral regions. Measured as the photon or energy flux for a specified waveband.

PPF (Photosynthetic Photon Flux) - The photosynthetic photons received on a horizontal surface and cosine corrected for angle of inception. Generally accepted to be wavelengths between 400 and 700 nm, but sometimes defined to include wavelengths as short as 350 nm and as long as 800 nm. The radiation units are photons and are commonly reported as $\mu mol\ m^{-2}\ s^{-1}$ ($6.02 \cdot 10^{17}$ moles photons $m^{-2}\ s^{-1}$).

PPFD (Photosynthetic Photon Flux Density) - Used synonymously with PPF (see PPF).

Pyroheliometer - A type of pyranometer that tracks the sun so that its absorbing surface is maintained perpendicular to solar radiation during the daylight period.

Pyranometer - A radiometer used for monitoring radiation and fitted with a protective glass filter dome that limits transmission to 280 to 2800 nm wavelengths.

Quantum - A packet of the smallest unit of radiation at a specific wavelength (plural, "quanta").

Radiation - Energy as electromagnetic waves propagated through free space at $3x10^8$ $m{\cdot}s^{-1}$ per second.

Radiometer - A general term used to describe any instrument that measures the energy of radiation.

Spectrum - The characteristics, including nomenclature, of electromagnetic radiation in relation to the wavelengths.

Spectral - Specific wavelength-related quantification.

Spectroradiometer - A radiometer designed to measure the radiation in narrow wavelengths of less than 10 nm (commonly 1, 2, or 5 nm bandwidths). The measurement is given in energy units and is reported as $J\ m^{-2}\ s^{-1}\ nm^{-1}$ or $W\ m^{-2}\ nm^{-1}$. Some instruments are programmed to provide calculation of photon and light units for the individual bandwidths.

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